

Calibration of the ISOLDE acceleration voltage using a high-precision voltage divider and applying collinear fast beam laser spectroscopy

A. Krieger^{a,*}, Ch. Geppert^{a,b}, R. Catherall^c, F. Hochschulz^d, J. Krämer^a, R. Neugart^a, S. Rosendahl^d, J. Schipper^c, E. Siesling^c, Ch. Weinheimer^d, D. T. Yordanov^e, and W. Nörtershäuser^{a,b}

^a*Institut für Kernchemie, Universität Mainz, 55128 Mainz, Germany*

^b*GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*

^c*CERN, CH-1211 Genève 23, Switzerland*

^d*Institut für Kernphysik, Universität Münster, 48149 Münster, Germany*

^e*Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*

Abstract

A high-voltage divider with accuracy at the ppm level and collinear laser spectroscopy were used to calibrate the high-voltage installation at the radioactive ion beam facility ISOLDE at CERN. The accurate knowledge of this voltage is particularly important for collinear laser spectroscopy measurements. Beam velocity measurements using frequency-comb based collinear laser spectroscopy agree with the new calibration. Applying this, one obtains consistent results for isotope shifts of stable magnesium isotopes measured using collinear spectroscopy and laser spectroscopy on laser-cooled ions in a trap. The long-term stability and the transient behavior during recovery from a voltage dropout were investigated for the different power supplies currently applied at ISOLDE.

Keywords: High voltage divider, Collinear spectroscopy, ISOLDE facility, Isotope shift, Magnesium

1. Introduction

The accurate determination of high voltages is crucial for a variety of atomic, nuclear and particle physics experiments. Examples are the acceleration voltage of ion beams for collinear laser spectroscopy [1], the energy of electrons in an electron cooler applied at storage rings to narrow the momentum distribution of the circulating ion beam [2, 3], or the voltage applied in a retardation spectrometer to determine the kinetic energy of electrons emitted in β -decay [4, 5]. Fast-beam experiments often require precise knowledge of the kinetic energy or the velocity of the beam particles, especially if resonance processes are investigated. On the other hand, such resonance processes can be used to measure the ion beam velocity. In this case, sharp resonances are preferred since the linewidth is one of the limiting factors for the accuracy that can be achieved. Collinear laser spectroscopy (CLS) on fast ion or atomic beams is a particularly clear example for both cases. In the

past, it has been used extensively for studying nuclear ground state properties of short-lived radioactive isotopes [7, 8, 9, 10, 11]. CLS utilizes the Doppler shift of the frequency of a light wave in the moving frame of an accelerated ion. Hence, a fixed-frequency laser can be brought into resonance and tuned across the transition frequency of the ion by changing the ion velocity. To extract information on isotope shifts and hyperfine splittings, accurate knowledge of this velocity, *i.e.* of the ion beam energy, is required. Typically, voltages of 30-60 kV are applied to the ion source. For most investigations of medium-mass and heavy nuclei, it is sufficient to know the voltage applied to the ion source and the potentials at secondary acceleration or deceleration stages with a relative accuracy of the order 10^{-4} . This is the level for which high-voltage dividers are commercially available. However, as it will be discussed in the first section of this paper, this accuracy is by far not sufficient for measurements on the very light elements reaching from hydrogen to roughly neon.

If the frequency of an atomic resonance is well known, CLS can be used (in reverse) to determine the ion velocity, hence, the kinetic energy and the voltage applied to the source. This has already been suggested

*Corresponding author at Institut für Kernchemie, Johannes Gutenberg - Universität Mainz, Fritz-Straßmann-Weg 2, 55128 Mainz, Germany.

Email address: kriegea@uni-mainz.de (A. Krieger)

by Poulsen in 1982 [12, 13]. The latest development along these lines was a test apparatus for measurements of high voltages up to a few 100 kV, to determine and calibrate the voltage of the electron cooler at the GSI experimental storage ring ESR [14]. The layout of the prototype allowed measurements up to 50 kV and the $3d_{3/2,5/2} \rightarrow 4p_{3/2}$ transitions in calcium ions were used for probing the ion velocity. It was demonstrated that accuracies in the order of 10^{-4} can be reached and suggestions for further improvement were made.

In this paper, we report on the calibration of the high-voltage dividers used at ISOLDE/CERN to measure the potential applied to the high-voltage platforms on which the ion sources are mounted. There are two independent units, HT1 and HT2, that can alternatively be used to provide and to measure acceleration voltages up to 60 kV. The calibration was performed using a non-commercial high-precision high-voltage divider with accuracy in the ppm range [6], and collinear laser spectroscopy on beryllium ions. Both approaches gave consistent results and the calibration resolved problems in the earlier analysis of isotope shift measurements on stable and radioactive magnesium isotopes. These problems could be traced back to differences in the measured voltages of HT1 and HT2, which in CLS translate into different Doppler shifts of the resonance frequency. We will start with a short summary of the principles of CLS and their implications for isotope shift measurements, and we will describe test measurements of absolute Doppler shifts to determine the ion velocity. Then, a concise description of the high-accuracy high-voltage divider will be given and the results of two calibration campaigns are discussed in results of the long-term as well as the transient behavior of the high-voltage supplies.

2. Collinear Laser Spectroscopy

CLS was proposed by Kaufman [1] and was rapidly developed into a useful tool, namely for the spectroscopy of short-lived radioactive isotopes. Its first on-line installation was realized at a nuclear research reactor [15] and soon thereafter the COLLAPS (collinear laser spectroscopy) beamline at the radioactive ion beam facility ISOLDE was built [16]. Followed by similar and more advanced experiments (see, *e.g.* [17, 18, 19, 20, 21]) collinear laser spectroscopy developed into a general technique for on-line investigations of spins, electromagnetic moments and nuclear charge radii of short-lived isotopes. It was continuously improved and combined with different detection techniques and, thus,

became increasingly sensitive and accurate. The latest steps in these developments where the combination of CLS with an RFQ cooler and buncher [22] and frequency-comb-based collinear spectroscopy [23, 24].

The scheme of our setup for CLS on an ion beam is shown in Fig. 1. An ion beam at a usual beam energy of 30-60 keV is superimposed with a laser beam in the collinear or anticollinear direction using an electrostatic deflector. In the figure the special layout for simultaneous collinear and anticollinear measurements with two laser systems is depicted, whereas in standard CLS only a single system is applied. Photons are collected in the fluorescence detection region (FDR) and detected by photomultiplier tubes or other devices capable of single-photon counting. Usually, the ions are accelerated or decelerated into this region, to prevent interaction with the laser light before they reach the FDR. Otherwise, multiple excitation will in most cases lead to optical pumping into dark states and hence diminish the detection sensitivity. Moreover, for two-level systems a long interaction region could also lead to changes in the ion velocity and therefore to undesired shifts in the observed resonance frequency.

Acceleration of the ions leaving the hot ion source region has two important consequences for CLS: First, it leads to a strong compression of the momentum distribution in the longitudinal phase space [1]. The Doppler width $\Delta\nu_D$ of an atomic transition with frequency ν_0 is normally caused by the thermal distribution of kinetic energies $E = mv^2/2$ of the atoms. For an ion beam the width of the energy distribution δE is determined by properties of the ion source *e.g.*, the potential distribution inside the source and the ionization process. By acceleration in an electrostatic field the energy spread

$$\Delta E = m v \Delta v \quad (1)$$

remains constant. Consequently, if the velocity v increases, the velocity spread δv has to decrease accordingly. By this effect, at energies of a few 10 keV, the Doppler width in the beam direction

$$\Delta\nu_D = \nu_0 \Delta v/c \quad (2)$$

is expected to be reduced to the order of the natural linewidth of a typical allowed dipole transition. With $v = \sqrt{2eU/m}$ given by the acceleration voltage U one obtains

$$\Delta\nu_D = \nu_0 \frac{\Delta E}{\sqrt{2eU}mc^2}. \quad (3)$$

The ion source conditions also influence the total energy of the accelerated beam. This has important consequences for high-voltage measurements and the accuracy in CLS: The potential applied externally to the

source is not necessarily identical with the potential at which ions are created. Three ion sources are typically used at ISOLDE: surface ion sources, the resonant ionization laser ion source (RILIS) and plasma ion sources. While for the former ones the uncertainty of the start potential of the ions is less than 3 V, in the plasma ion sources it can be an order of magnitude larger. Hence, high-voltage measurements more accurate than about 20 ppm are inappropriate and will not help to obtain higher accuracy. All measurements reported here were performed with ions from RILIS.

The second consequence of acceleration is a large Doppler shift of the atomic transition frequency according to

$$\nu_c = \nu_0 \gamma (1 \pm \beta) \quad (4)$$

in the case of collinear excitation and anticollinear excitation, respectively. Here, $\gamma = \sqrt{1 - \beta^2}$ is the relativistic time dilatation factor and $\beta = v/c$ is the ion velocity in units of the speed of light. The standard procedure in CLS is as follows: The laser frequency is fixed at ν_L close to the Doppler-shifted resonance frequency ν_c and the velocity of the ions is changed until the varying Doppler shift of the laser frequency brings the atomic transition into resonance with the laser light. The atomic resonances of isotopes with masses m_1 and m_2 occur at different voltages $U^{(1)}$ and $U^{(2)}$ fulfilling the condition

$$\begin{aligned} \nu_L &= \nu_0^{(1)} \frac{m_1 c^2 + eU^{(1)} \pm \sqrt{eU^{(1)}(2m_1 c^2 + eU^{(1)})}}{m_1 c^2} \\ &= \nu_0^{(2)} \frac{m_2 c^2 + eU^{(2)} \pm \sqrt{eU^{(2)}(2m_2 c^2 + eU^{(2)})}}{m_2 c^2} \end{aligned} \quad (5)$$

with $\nu_0^{(2)} = \nu_0^{(1)} + \delta\nu_{\text{IS}}^{1,2}$, where $\delta\nu_{\text{IS}}^{1,2}$ denotes the isotope shift. One should remember that $eU^{(i)}$ refers to the beam energy and not necessarily to the applied ion source potential. We will first consider the case that the complete acceleration voltage is measured with a miscalibrated voltage divider. Using the approximation $\nu_0^{(1)} \approx \nu_0^{(2)}$, because $\delta\nu$ is usually small compared to ν_0 , we obtain

$$U^{(2)} = \frac{m_2}{m_1} U^{(1)}. \quad (6)$$

A common calibration factor in the voltage measurement will cancel out on both sides. Hence, only a small error occurs due to the slightly different resonance frequencies which even in the case of beryllium with a large isotope shift and a small mass is less than 1 MHz for a 10^{-4} voltage deviation. However, it is standard in CLS - because mass separators are used - that the total acceleration voltage is composed of the source potential which is used to generate the fast ion beam, and a

smaller variable potential at the fluorescence detection region used for Doppler tuning. The resulting influence of voltage errors is much larger in this case. We first solve the relation $\nu_0^{(2)} = \nu_0^{(1)} + \delta\nu_{\text{IS}}^{1,2}$ to extract a fully relativistic formula for the isotope shift and obtain

$$\begin{aligned} \delta\nu_{\text{IS}}^{1,2} &= \frac{\nu_0}{\kappa} \left\{ m_2 \left(eU^{(1)} + \sqrt{eU^{(1)}(2m_1 c^2 + eU^{(1)})} \right) \right. \\ &\quad \left. - m_1 \left(eU^{(2)} + \sqrt{eU^{(2)}(2m_1 c^2 + eU^{(1)})} \right) \right\} \end{aligned} \quad (7)$$

where $\kappa = m_1 \left[m_2 c^2 + eU^{(2)} + \sqrt{eU^{(2)}(2m_2 c^2 + eU^{(2)})} \right]$. The effect of a calibration error in the isotope shift measurement can now easily be calculated by replacing $U^{(1)}$ and $U^{(2)}$, with voltages

$$U^{(i)'} = U_{\text{Source}}^{(i)} (1 + k_{\text{Source}}) + U_{\text{FDR}}^{(i)} (1 + k_{\text{FDR}}), \quad (8)$$

where $i = 1, 2$. The unprimed values are the real voltages and the primed values are the measured voltages, with miscalibration factors k_{Source} for the source and k_{FDR} for the fluorescence detection region. In Table 1, the results of these calculations are summarized under the following assumptions which are typical for measurements at ISOLDE but also for CLS at other facilities: The ISOLDE ion source potential is assumed to be $U_{\text{Source}} = 50$ kV and the laser frequency is chosen in such a way that the resonances of two isotopes with mass numbers A and $A + 2$ occur symmetrically at post-acceleration voltages $+U_{\text{FDR}}$ and $-U_{\text{FDR}}$. At COLLAPS the post-acceleration voltage U_{FDR} can be up to ± 10 kV. For the measurement this voltage range depends on the hyperfine structure to be scanned. For the ISOLDE miscalibration factor we assume $k_{\text{Source}} = 0.0001$ which lies within the specified accuracy of 10^{-4} . We further assume that U_{FDR} is measured exactly, hence, $k_{\text{FDR}} = 0$. The resonances of both isotopes therefore appear at measured voltages $U^{(i)'} = 50005 \text{ V} \pm U_{\text{FDR}}$. With these conditions the approximate error formula [16] for the isotope shift becomes

$$\Delta\delta\nu_{\text{IS}}^{1,2} = \nu_0 \sqrt{\frac{eU}{2mc^2}} \left(\frac{U_{\text{FDR}}^{(1)} - U_{\text{FDR}}^{(2)}}{2U_{\text{Source}}} + \frac{(m_2 - m_1)}{m_1 + m_2} \right) k_{\text{Source}} \quad (9)$$

We have calculated the effect for three elements that have been recently investigated at ISOLDE. The most crucial case is beryllium. Here, an accuracy of about 1 MHz is required to extract the nuclear charge radius of the neutron halo isotope ^{11}Be [23] with sufficient accuracy and it is obvious that this accuracy cannot be reached in the standard approach. For magnesium, the voltage accuracy of 10^{-4} barely meets the requirements, while in the case of copper the standard voltage divider

Table 1: Calculations of the influence of high-voltage calibrations on isotope shift measurements for light and medium mass nuclei. Ion masses are used as integer numbers, the transition frequencies refer to the $2s_{1/2} \rightarrow 2p_{1/2}$, the $3s_{1/2} \rightarrow 3p_{3/2}$, the $3s_{1/2} \rightarrow 3p_{1/2}$ transition in Be^+ , Mg^+ and Cu^+ , respectively. $\delta\nu_{\text{IS}}^{A,A+2}$ is the complete isotope shift between the two isotopes with mass numbers A_1 and A_2 . The differential isotope shift $\partial\nu/\partial U(A)$ was calculated according to Eq. (10) and $\Delta\delta\nu_{\text{IS}}^{A,A+2}$ gives the artificial isotope shift introduced by a 10^{-4} measurement error on the acceleration voltage. The last column indicates the typically required accuracy on the isotope shift measurement to extract charge radius information. For more details see text.

Isotope pair	$\nu_0(A)$ (THz)	$\delta\nu_{\text{IS}}^{A,A+2}$ (MHz)	$\partial\nu/\partial U(A)$ (MHz/V)	$\Delta\delta\nu_{\text{IS}}^{A,A+2}$ (MHz)	Required accuracy (MHz)
$^9\text{--}^{11}\text{Be}$	957.22	14240.0	31.2	29.2	1
$^{24}\text{--}^{26}\text{Mg}$	1072.08	3220	22.5	8.5	3
$^{63}\text{--}^{65}\text{Cu}$	923.01	2000	11.9	1.7	5

is sufficient. If charge radii for two or more isotopes are available from other techniques, for example muonic atom spectroscopy, the requirements are slightly less severe. The systematic error caused by the voltage miscalibration behaves largely as the mass shift. Hence, the King plot procedure used in such cases, delivers a mass shift constant that will result in a correct field shift evaluation. However, for the lightest nuclei even this approach does not provide sufficient accuracy.

In summary, CLS of light elements is difficult because the ions have a large differential Doppler shift

$$\frac{\partial\nu}{\partial U} = \frac{\nu_0}{mc^2} \left(e + \frac{e(mc^2 + eU)}{\sqrt{eU(2mc^2 + eU)}} \right) \approx \frac{e \cdot \nu_0}{\sqrt{2eUmc^2}} \quad (10)$$

and the observed resonance positions are therefore extremely sensitive to the applied voltage and thus to voltage fluctuations. Moreover, the mass shift in these isotopes is huge compared to the tiny nuclear volume effects. Nevertheless, a few techniques were developed to overcome these problems and allowed CLS of a few, particularly interesting cases. CLS of short-lived neon isotopes including the two-proton halo candidate ^{17}Ne was performed using a special feature of the neon atomic spectrum: Two fine-structure transitions in neon starting from a common metastable level, which was populated in charge exchange collisions, have a splitting that fits exactly to the opposite Doppler shifts in collinear and anticollinear excitation at a beam energy of about 61.8 keV if the laser frequency is set to the average transition frequency in the rest frame. This was used in the neon measurements at COLLAPS to calibrate the beam energies and to obtain reliable isotope shift values for the neon isotopes [25, 26]. In this experiment, good agreement between the applied high voltage at ISOLDE and the beam energy was found. On Li^+

ions Riis and coworkers [27] used collinear and anti-collinear saturation spectroscopy, which is not sensitive to an exact match of the ion velocity with the optical resonance. Such a type of spectroscopy is also used for Ives-Stilwell tests of Special Relativity at storage rings [28, 29]. Here, the rest frame frequency is obtained from the observed Lamb dips using the product formula of Eq. (4):

$$\nu_0^2 = \nu_c \cdot \nu_a, \quad (11)$$

with ν_a and ν_c being the laser frequencies at the resonance position in anticollinear and collinear geometry, respectively. This relation is independent of all applied voltages but requires knowledge of the absolute laser frequencies typically on the $10^{-9} - 10^{-10}$ scale. In the lithium experiment [27], this was performed using iodine reference lines and the isotope shift of the two stable isotopes $^6,7\text{Li}$ was extracted with good accuracy. To avoid uncertainties of the voltage measurement and to determine the isotope shift between $^7,9,10,11\text{Be}$, as well as the absolute excitation frequencies ν_0 for the $2s_{1/2} \rightarrow 2p_{1/2,3/2}$ transitions with an accuracy better than 2 MHz, a similar approach was used for the first time in an on-line experiment. A detailed discussion of the laser system and experimental setup is given in [23, 24]. Summarized, as shown in Fig. 1, two dye lasers were collinearly and anticollinearly overlapped with a beryllium ion beam. For precise frequency determination and stabilization one laser was locked to a frequency comb, the second one to an iodine transition via Doppler-free frequency modulation saturation spectroscopy in an iodine cell. From two second-harmonic generation devices, UV light of 312 nm and 314 nm was coupled through quartz windows into the collinear and anticollinear directions of the ion beam, respectively. The observed resonance frequencies ν_a and ν_c allowed us to determine the absolute transition frequency ν_0 in the rest frame of the ion according to Eq. (11). The

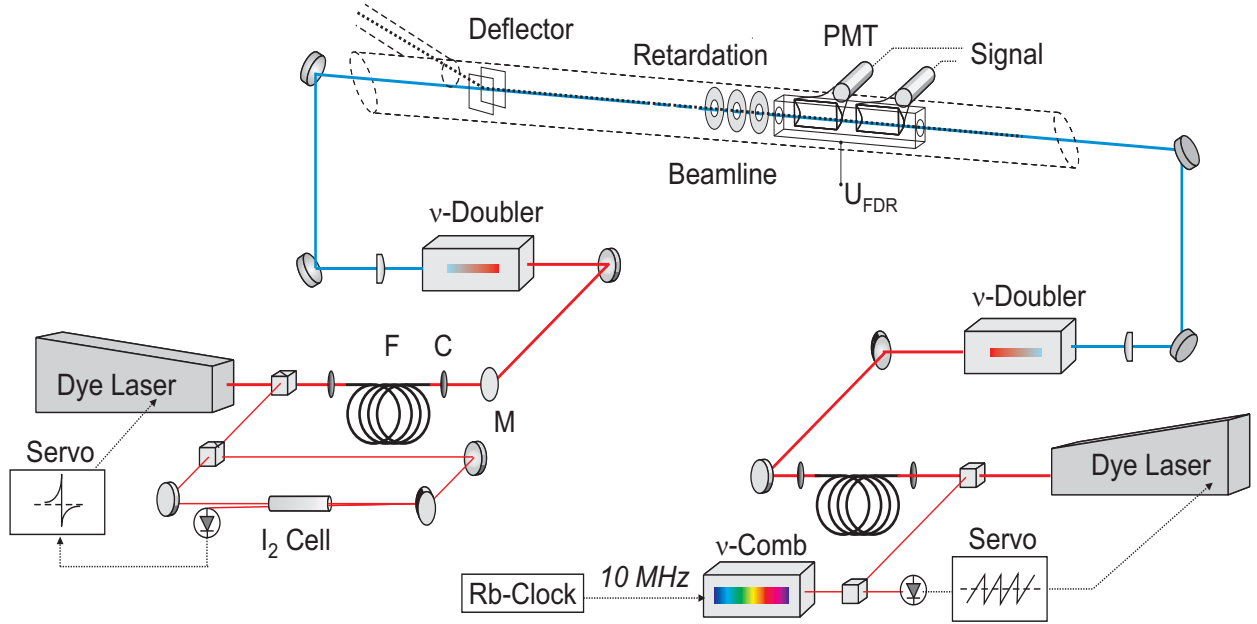


Figure 1: Experimental setup for collinear and anticollinear spectroscopy on fast Be^+ -ions at ISOLDE. Two fiber-coupled dye lasers seed second-harmonic generator rings producing UV light at wavelengths of 312 nm and 314 nm respectively. The laser beams are superimposed collinearly and anticollinearly with the ion beam. Scanning over a resonance is achieved by applying a small stepwise voltage U_{FDR} to the fluorescence detection region FDR. region FDR

isotope shift was then extracted as the difference of the absolute transition frequencies between different isotopes. Then the inversed process was used and from the now known value of ν_0 for ^9Be and the collinear and anticollinear signal the beam energy was determined with an accuracy at the level of 10^{-5} using Eq. (4).

The relative difference between the beam energy and the ISOLDE high-voltage readings were found to be $-2.0(2) \cdot 10^{-4}$ for the power supplies HT1 and $6.5(4) \cdot 10^{-4}$ for HT2, corresponding to absolute values of $-12(1.3)(3.0)$ V and $39.0(2.4)(3.0)$ V at the maximum operation voltage of 60 kV. Here the first uncertainty denotes the pure fitting uncertainty and the second one the systematic uncertainty. This systematic uncertainty accounts for the limited knowledge about the potential at which ionization takes place in the source. Both devices, including the high-voltage dividers, were installed at ISOLDE in 1981 and are in operation since then. More details will be given in Section 3.

Since we found a clear discrepancy between the measured ISOLDE ion source voltages and the beam energy, we attributed this to a problem in the high voltage readout. Therefore, a recalibration of the ISOLDE high-voltage divider was arranged for future

CLS experiments using an independent high-precision voltage divider.

3. The high-voltage installation at the ISOLDE facility

The on-line mass separator ISOLDE at CERN produces low-energy radioactive ion beams [30] making use of the so called ISOL¹ technique: A stack of four synchrotrons, the Proton Synchrotron Booster (PSB), produces a pulsed 1.4 GeV proton beam. These high-energy protons are delivered to one of the two target stations, inducing nuclear reactions in a thick target to produce radioactive isotopes. The reaction products are ionized, *e.g.* via resonant laser ionization at about 2000 °C [31, 32]. The targets and ion sources are mounted on two platforms of positive electrical potential up to 60 kV. The ions are then extracted and accelerated to ground potential for mass separation. For that purpose either the General Purpose Separator GPS or the High Resolution Separator HRS magnetic sector separator can be used. The mass separated ion beam is guided to the experiments.

¹isotope separation on-line

The target and ion source platform is connected to either of two units HT1 or HT2 comprising a stabilized HV power supply and a voltage divider for the readout of the applied ion source potential. The high voltage circuitry of each unit is shown in Fig. 2. Up to 2008 the acceleration voltage was generated by two actively regulated ASTEC 60 kV precision power supplies. The accuracy of both was specified to 10^{-4} . The internal voltage stabilization feedback loop is based on a ROSS voltage divider 75-10-BDL, represented by resistors R7a/R7b in Fig. 2, using a scale factor 1000:1. In order to stabilize the devices in temperature to ± 0.1 K the power supplies, the resonant circuit and the ROSS voltage divider were immersed in an oil bath.

A similar ROSS voltage divider at a scale factor of 10000:1, represented by resistor R8a/R8b and a high-precision HP 3458A digital multimeter (6 1/2 digit resolution, which corresponds to an accuracy of 10^{-5}) are used to read out the stabilized target voltage to the ISOLDE control system via GPIB. These dividers were originally specified with an accuracy of 10^{-4} and a stability of $5 \cdot 10^{-5}$ per year.

In 2009 the former ASTEC power supply of HT1 was replaced by a self-regulated Heinzinger power supply of the PNChp3p series. In this commercial device the applied voltage is regulated internally and specified in stability to $1 \cdot 10^{-5}$ over a time period of 8 hours under constant conditions and in load regulation, and for a load step from zero to the nominal voltage, to $5 \cdot 10^{-4}$. For readout the ISOLDE control system uses again the ROSS voltage divider and HP 3458A multimeter, *i.e.*, resistors R8a/R8b in Fig. 2.

During proton beam impact, the ionization of the air volume around the target gives rise to a significant leakage current which results in loss of charge on the effective target capacitance. This voltage breakdown could lead to damage of the HT supply and furthermore can significantly slow down the regulation loop, hence the reason of blanking the high voltage by a resonant circuit [33]. The principle task of this resonance circuit is to fully discharge the target capacitance prior to beam impact. The schematic is included in the upper right part of Fig. 2: The first pole of the pulse transformer is connected to a commercial power supply (FuG Elektronik, 0-15 kV), whose output voltage is a function of the ASTEC's output voltage, controlled by a thyatron, which is synchronously triggered with the PSB ejection kickers. The current supplied by the resonant circuit discharges through the capacitance of the target. Thus, a high-voltage pulse of up to 60 kV with opposite polarity modulates the target voltage (within $30 \mu\text{s}$) to zero, just before the protons collide with the target. A small

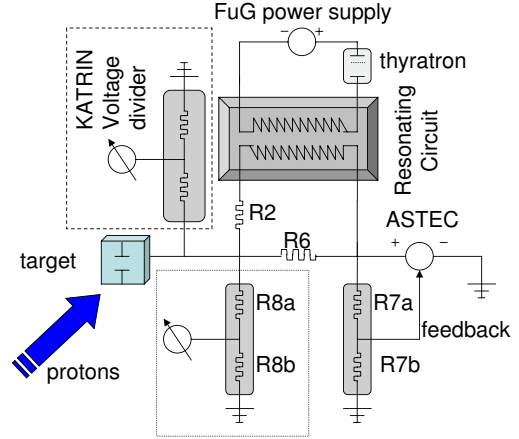


Figure 2: Simplified schematic view of the high voltage circuitry at the two ISOLDE HV units including a resonant circuit used to modulate the high voltage applied to the target. The resistors R7a/R7b represent the ROSS voltage divider for internal stabilization whereas R8a/R8b (framed) represent the voltage readout U_{ISOLDE} .

resistor R2 ($=250 \Omega$) reduces the stabilization time to less than 10 ms after the pulse for ± 1 V from the nominal voltage. At this point a voltage drop of $R2 \cdot I$ is at most 500 mV. The resistor R6 ($=1.5 k\Omega$) forms a fast coupling of the ASTEC supply to the target. Note, that the power supply itself is running in a static mode and that only the acceleration gap receives the modulated voltage. The figure shows also the connection to the high-precision Karlsruher Tritium Neutrinoexperiment (KATRIN) dividers used for calibration.

4. The High-Precision Voltage Divider

Although small voltage differences can be measured to the highest precision, *e.g.* 10^{-12} applying the Josephson effect [34, 35], measuring high-voltages at precision levels below 10^{-4} becomes increasingly difficult. To measure voltages larger than 10 kV with high accuracy, voltage dividers are required to downsize the voltages to a range accessible for a precise digital multimeter. A high-precision voltage divider, further denoted K1 [6], was developed for the Karlsruher Tritium Neutrinoexperiment KATRIN [36], which is able to determine voltages up to 35 kV in the sub-ppm regime. The KATRIN experiment measures the mass of the electron neutrino directly with highest sensitivity in the sub-eV regime using a so-called MAC-E-Filter (magnetic adiabatic collimation combined with an electrostatic filter). Thus high luminosity and energy resolution are combined in order to determine the

Table 2: Calibration parameters of the Karlsruher Tritium Neutrinoexperiment (KATRIN) dividers K1 and K2 derived at Physikalisch Technische Bundesanstalt (PTB) [6]. A first calibration campaign at PTB demonstrated that divider K2 shows even higher stabilities of the scale factor with respect to time, voltage and temperature, but not all investigations are finished yet, therefore the K2 calibration values are still preliminary. For details see text.

Parameter	divider K1	divider K2
Absolute scale factor K_0 as of Nov 2006 (K1), Dec 2009 (K2)	3944.9597(14)	3636.2743
Long-term stability of scale factor $c_t := \frac{\partial K}{\partial t} \cdot \frac{1}{K}$	$6 \cdot 10^{-7} \text{ month}^{-1}$	
Temperature dependence of scale factor at $T = 25^\circ \text{C}$ $c_T := \frac{\partial K}{\partial T} \cdot \frac{1}{K}$	$1.7(7) \cdot 10^{-7} \text{ K}^{-1}$	$1 \cdot 10^{-7} \text{ K}^{-1}$
Voltage dependence of scale factor at $U = 18.6 \text{ kV}$ $c_U := \frac{\partial K}{\partial U} \cdot \frac{1}{K}$	$-2.8(2) \cdot 10^{-8} \text{ kV}^{-1}$	$-1.9(2) \cdot 10^{-8} \text{ kV}^{-1}$
Quadratic voltage dependence $c_{UU} := \frac{\partial^2 K}{\partial U^2} \cdot \frac{1}{K}$	$-7.5(4) \cdot 10^{-10} \text{ kV}^{-2}$	

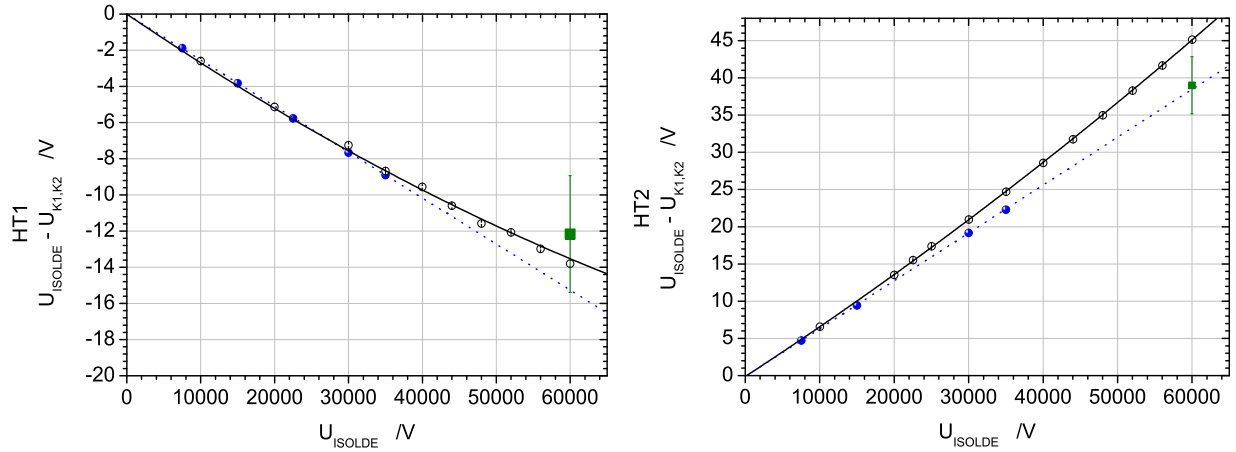


Figure 4: Discrepancy between the readout of the ISOLDE high-voltage power supplies HT1 and HT2 and the voltage determined by the KATRIN voltage dividers K1 (● up to 35 kV, 2008) and K2 (○ up to 60 kV, 2009). Parabolic functions are fitted to the 2009 data and linear functions (dashed line) to the 2008 data. The latter was extrapolated to 65 kV. The result of a beam energy measurement at 60 kV using collinear laser spectroscopy is shown for comparison (■ at 60 kV, 2008).

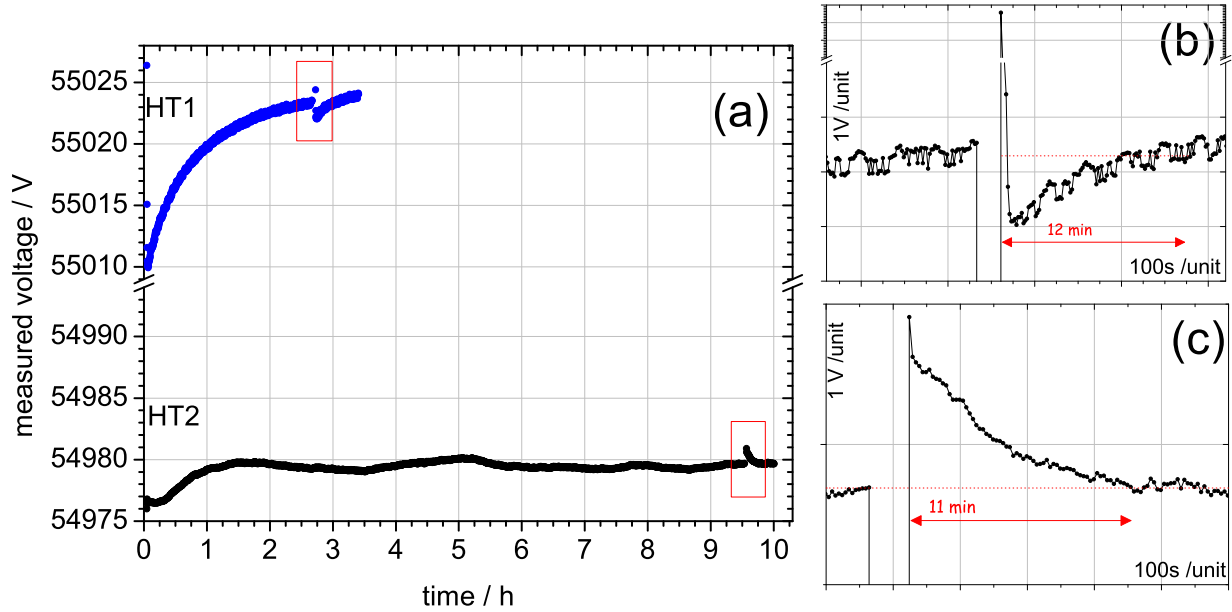


Figure 5: (a) Long-term behavior of the high-voltage unit HT1 at ISOLDE equipped with the Heinzinger power supply (upper trace, top axis 3 h) and HT2 equipped with the ASTEC device (lower trace, bottom axis 10 h) for a set potential of 55 kV recorded with the KATRIN K2 divider. A short abrupt voltage drop as it occurs at ISOLDE occasionally was induced on purpose in the regions indicated by the boxes, to investigate the transient behavior after resetting the HV. This region is enlarged in the graphs (b) for HT1 and (c) for HT2.

energy distribution of the electrons at the end-point of a tritium β -decay. The precision of this energy measurement relies on the ppm precision of the applied electrostatic retarding potential.

One year later, in 2009, a second high-precision divider K2 for the KATRIN experiment was completed to measure high voltages up to 65 kV. Both dividers were specified at the Physikalisch Technische Bundesanstalt (PTB) to sub-ppm accuracy and stability. We report here on a voltage calibration of the two ISOLDE high voltage units HT1 and HT2 against these high-precision voltage dividers.

Figure 3 shows a picture of the K1 divider: A cylindrical stainless steel container with a diameter of 60 cm and a height of 85 cm houses the voltage divider setup. The case, which shields from electromagnetic interference from outside, is flooded with N_2 gas at atmospheric pressure along the resistors for insulation and temperature stabilization at $25 \pm 0,15$ C. The interior consists of five copper ring electrodes fixed by polyoxymethylene rods which are concurrently used as insulators. The heart of the voltage divider is the primary resistor chain, which consists of 106 precision resistors of Bulk Metal Foil technology² with a total

resistance of $184 \text{ M}\Omega$ [6]. These resistors are arranged in a helix structure between the copper electrodes. Up to the fourth one, each ring comprises 25 resistors. The low voltage output is formed by the remaining six resistors arranged in each case by three resistors in parallel. Thus a scale factor of 3945:1 or 1972:1 can be provided. The copper electrodes generate a constant electric field along the primary high-precision resistor chain. A secondary resistor chain of four high-voltage $44 \text{ M}\Omega$ resistors (Caddock MX480) connects each pair of copper electrodes to provide a linear potential distribution. In order to protect the primary resistors against transient overloads a capacitive chain, consisting of four 2.5 nF capacitors (Vishay MKT1816), is implemented between the copper electrodes. The high voltage to be measured is fed into a sealed HV bushing located at the top electrode.

The first version of the voltage divider setup K1 used in 2008 and described above, was limited to voltages up to 35 kV. The development of a further voltage divider K2 was strained to exceed K1 in disciplines of long-term stability and temperature stabilization behavior. Since the electric strength has already been increased to 65 kV (it is conceivable that potentials up to 100 kV could be measured, since the electric strength of the primary resistor chain is 100 kV, but the design

²BMF is a brand of Vishay Intertechnology Inc.:www.vishay.com

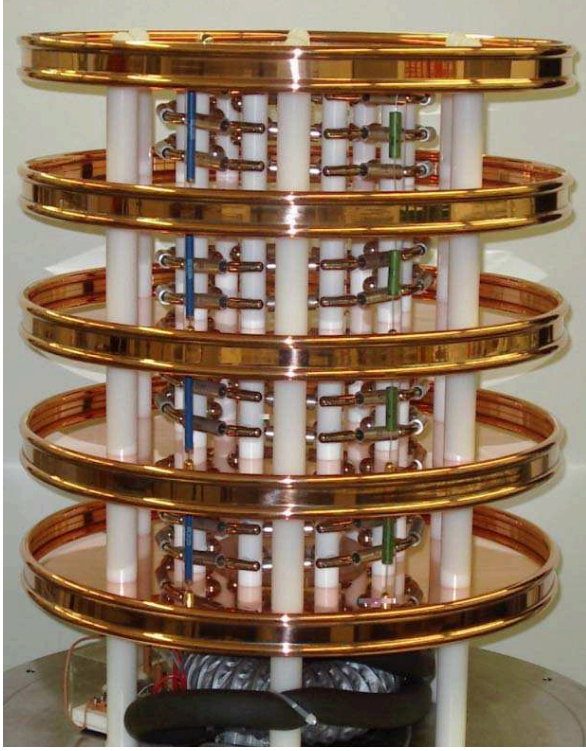


Figure 3: The interior of the high-voltage divider K1 from the Karlsruhe Tritium Neutrinoexperiment (KATRIN) experiment: 106 precision resistors with a total resistance of 184 M Ω are arranged in a helix structure around five copper ring electrodes and connects each pair of copper electrodes to provide a linear potential distribution over the primary high-precision resistor chain. Each pair of copper electrodes is connected by a high voltage resistor (blue) and capacitor (green) to control the electrical potential over the primary resistor chain and to protect it against overloads.

would have to be modified and tested), the K2 divider is suitable to cover the full range of the acceleration potential of the ions at ISOLDE. As both dividers are identical in concept, we mention only the major changes in the setup of K2: The copper ring electrodes divide the setup into five (instead of four) sections, where each section comprises 34 precision resistors of 880 k Ω . In the last, sixth level the low voltage outputs provide divider ratios of 3636:1, 1818:1 and 100:1. The first one is used for the calibrations reported here. The secondary divider chain connects the copper electrodes and comprises 5 resistors (Caddock MX480), each with 36 M Ω and a 90 k Ω resistance (Caddock MS260) in the sixth subsection for the voltage output. The tertiary capacitive chain consists of a series of 5 capacitors of 7.5 nF (3 capacitors of 2.5 nF in parallel).

Both voltage dividers were specified at the PTB (see Table 2). The divided voltage is measured by a FLUKE

8508A digital reference multimeter. In order to avoid drifts within this precision voltmeter, a 10 V reference potential was provided by a Fluke 732A reference voltage source, that also had been calibrated at the PTB. Before every calibration measurement, the digital voltmeter was calibrated with this 10 V reference.

5. High-voltage measurements

The following section describes the calibration measurements as well as the investigation of the transient behavior of the power supplies. Finally, the importance of the calibration is demonstrated with a result of collinear laser spectroscopy on stable magnesium isotopes.

5.1. Calibration measurements

For calibration of the high-voltage units HT1 and HT2 the voltage readout of ISOLDE was compared to the simultaneously measured voltage with the precision voltage divider K1 in 2008 and K2 in 2009. Both power supplies were switched on more than three hours before the measurement started, to make sure that thermal equilibrium was reached. The output of the power supply was then raised stepwise from 10 kV to 35 kV (K1) and to 60 kV (K2) and decreased again. After setting a new voltage, the system was given a period of 7 minutes to thermalize, before 3 data points were taken in a sequence of 30 seconds.

The high voltage U_{DIV} is given by the scale factor of the divider K times the low-voltage reading U_{lv} of the digital voltmeter (DVM). The latter is corrected for an offset δU_{lv} and a gain factor k close to 1, which is determined by the reference voltage source.

$$U_{\text{DIV}} = K \cdot (U_{\text{lv}} - \delta U_{\text{lv}}) \cdot k, \quad (12)$$

resulting in a voltage uncertainty of

$$\frac{\Delta U_{\text{DIV}}}{U_{\text{DIV}}} = \sqrt{\left(\frac{\Delta K}{K}\right)^2 + \left(\frac{\Delta k}{k}\right)^2 + \left(\frac{\Delta U_{\text{lv}}}{U_{\text{lv}}}\right)^2} \approx \frac{\Delta K}{K}. \quad (13)$$

This simplification is allowed because the relative uncertainties of the gain factor k of the DVM and of the voltage reading U_{lv} are smaller than 10^{-6} .

The scale factor of the divider K is derived from the factor obtained at the calibration date K_0 according to

$$K = K_0 \cdot (1 + c_t \cdot \delta t + c_T \cdot \delta T + c_U \cdot \delta U + c_{UU} \cdot \delta U^2) \quad (14)$$

by considering its long-term drift c_t over a time interval δt after the last calibration, its temperature and its

voltage dependence with δT being the temperature difference to the reference temperature of 25 °C, and δU being the voltage difference to the reference voltage 18.6 kV (see Table 2). The terms $c_T \cdot \delta T$, $c_U \cdot \delta U$ and $c_{uu} \cdot \delta U^2$ are smaller than 10^{-6} , therefore these corrections are neglected in our voltage measurements. Contrary, the long-term drift of divider K1 has been determined to be $c_t(K1) = 6 \cdot 10^{-7} \text{ month}^{-1}$ (see Table 2). Therefore the correction $c_t \cdot \delta t$ is significant ($\delta t \approx 24$ months) and is applied to our measured values. For divider K2 no long-term drift has been found yet and since $\delta t = 1$ month no correction is applied. To be conservative we assume a total long-term drift correction uncertainty of $\Delta(c_t \cdot \delta t) = 3 \cdot 10^{-6}$ for both dividers K1 and K2. The uncertainty of the high-voltage determination by the dividers K1 and K2 can be calculated as

$$\begin{aligned} \frac{\Delta U_{\text{DIV}}}{U_{\text{DIV}}} &= \frac{\Delta K}{K} \\ &\approx \sqrt{\left(\frac{\Delta K_0}{K_0}\right)^2 + (\Delta(c_t \cdot \delta t))^2} \\ &= 4 \cdot 10^{-6} \end{aligned} \quad (15)$$

The differences between the ISOLDE HT1 and HT2 readout and that of the KATRIN K1 and K2 dividers are plotted in Fig. 4 as a function of the applied voltage. Each data point is the average value of three subsequent measurements as described above. The tiny error bars, mostly covered by the data points, show the standard deviation of these 3 points. Note that in 2008 the calibration could only be carried out up to 35 kV due to the limited operating range of the K1 divider, while the 2009 calibration was performed up to 60 kV directly using K2. Furthermore, after the measurements in 2008 the ASTEC power supply of HT1 was replaced with the conceptionally modern Heinzinger device.

The linear function $y = ax$ between the voltage deviation ΔU and the ISOLDE reading U is obtained from a fit to the 2008 data (●) and is given by

$$\Delta U = -2.540(24)(40) \cdot 10^{-4} \cdot U. \quad (16)$$

The first uncertainty of the slope is the pure fitting error, while the second one denotes the systematic uncertainty according to Eq. (15). Linear extrapolation to an operation voltage of 60 kV thus results in a deviation of $-15.24(15)(24)$ V.

This deviation can be compared to the laser-spectroscopic beam energy measurement described in Sec. 2 that yielded a difference of $-12.0(13)(30)$ V at 60 kV. This data point is also included in Fig. 4 (■).

Note that laser spectroscopy determines the ion velocity via the Doppler shift, which depends on the starting potential of the ions inside the ion source. Therefore a small offset of about 1-3 Volts (systematic uncertainty) was expected corresponding to the potential gradient along the electrothermically heated tube in which ionization takes place [37]. Within this, both the laser and the voltage divider measurements are in reasonable agreement.

The calibration measurements in 2009 (○) are better reproduced with a second-order polynomial function

$$\begin{aligned} \Delta U &= -2.791(23)(40) \cdot 10^{-4} \cdot U \\ &\quad + 8.860(52) \cdot 10^{-10} \cdot U^2. \end{aligned} \quad (17)$$

This yields a deviation of $-13.55(16)(24)$ V at 60 kV. Note that the systematic uncertainty of the second order term in Eq. (17) is negligibly small. Since the 2009 calibration agrees in the region from 0-30 kV with the one from 2008, it can be concluded that a second-order polynomial calibration curve is probably also valid for the old data and even reduces the difference between the laser-based and the high-voltage measurement.

The ROSS voltage dividers used with the ASTEC devices were specified in 1989 to an accuracy of 10^{-4} corresponding to 6 V at 60 kV. The observed discrepancy is about twice that value which might be ascribed to aging effects over years. The fact that both measurements show the same deviation indicates that the internal regulation circuits of both power supplies are accurate.

The results of the investigation of the ISOLDE HT2 unit are shown in Fig. 4. The measurements taken in 2008 with the KATRIN K1 divider are fitted with the linear function $y = ax + b$ (dashed line), yielding:

$$\Delta U = +6.432(26)(40) \cdot 10^{-4} \cdot U - 0.128(68) \text{ V}, \quad (18)$$

which corresponds to an extrapolated voltage deviation of $+38.45(22)(24)$ V at the acceleration voltage of 60 kV. In this case we had to assume a linear function with a free offset to reproduce the data points. Laser spectroscopy at 60 kV yielded a deviation of $+39.0(24)(30)$ V which is in excellent agreement with the value obtained from the voltage calibration.

The calibration results in 2009 (○) were best reproduced by a second-order polynomial function of the form $y = a_1x + a_2x^2 + b$, yielding

$$\begin{aligned} \Delta U &= -0.118(39) \text{ V} + 6.51(46)(40) \cdot 10^{-4} \cdot U \\ &\quad + 1.721(69) \cdot 10^{-9} \cdot U^2 \end{aligned} \quad (19)$$

from the ISOLDE HT2 readout.

Here, a deviation of $+45.13(56)(24)$ V at the maximum operation voltage of 60 kV is observed, corresponding to a relative deviation of $8 \cdot 10^{-4}$. As already mentioned earlier, studies with the previous voltage divider K1 allowed measurements up to 35 kV only. Within this limit no significant difference between a linear or parabolic fit was found. However, the K2 calibration measurements up to 60 kV are clearly incompatible with a linear function and require a second-order polynomial fit. Moreover, the 2008 and 2009 data differ considerably even in the region between 0-35 kV which indicates an appreciable instability of the ISOLDE HT2 high-voltage divider.

In a direct comparison applying a second-order parabolic fit to the 2008 measurement with K1 similar to the recent measurements with the K2 divider (2009), one observes a discrepancy of 6.7 V at the maximum voltage of 60 kV. This corresponds to a surprisingly large change of $1.2 \cdot 10^{-4}$ over an interval of 18 months between both calibrations. Therefore, the HT2 unit, in particular the associated ROSS divider, should not be used for collinear laser spectroscopy before further investigations of the day-to-day and long-term behavior have been performed.

5.2. Voltage stability and transient behavior

For all experiments depending on the ion beam energy, for example laser spectroscopy or injection into ion traps, the stability of the beam energy is essential. Hence the stability was investigated in a long-term measurement, using the K2 divider in 2009. Both power supplies, HT1 and HT2, were switched on several hours in advance and were operated at 10 kV. Then the voltage was increased in one step to 55 kV and recorded as a function of time. For both units we also simulated a voltage dropout as it occasionally occurs at ISOLDE due to sparking or a leakage current on the target. Therefore, we switched the power supply to "standby" and after one minute back to 55 kV.

As visible on the very left of the large graph in Fig. 5, the Heinzinger power supply at HT1 (upper trace) responds with a large, but short overshoot after setting a new voltage. Within 3 hours it increases by more than 14 V and asymptotically reaches a stable voltage. A high resolution zoom shows that the power supply regulates in steps of about 200 mV to a temporary "stable" potential. This leads us to the conclusion that the regulation circuit of the Heinzinger power supply itself is working well, but the voltage feedback measurement within the Heinzinger power supply needs several hours

to thermalize or stabilize. After the short voltage drop, induced within the indicated box, the original potential is restored within 12 minutes. During these 12 minutes an initial deviation of about 1 V is slowly being removed. This is clearly observable in the zoom shown in Fig. 5(b).

The lower trace in Fig. 5 shows a similar long-term measurement of the ASTEC voltage stability of the HT2 unit. After turn-on, it starts smoother than the Heinzinger at HT1, with a deviation of about 3 V from the stationary voltage which is reached within 1 hour. Similarly to the Heinzinger, the ASTEC power supply circuit at HT2 responds to the voltage drop with an overshoot after reinitializing the device and takes about 11 minutes to regulate back to a maximum deviation of about 1 V from the average output voltage. The knowledge of this behavior is particularly important for laser spectroscopy. Scans performed shortly after a voltage drop may systematically deviate from those taken with a well-stabilized voltage and produce additional errors on the isotope shifts. Therefore it should be avoided to take data within about 10 min after reinitialization of the high voltage, otherwise systematic shifts in the resonance positions may occur.

5.3. Implications of the new calibration for laser spectroscopy measurements on magnesium isotopes

The importance of the high-voltage calibration for collinear laser spectroscopy was demonstrated in our recent isotope shift measurements on stable and short-lived Mg isotopes $^{21-32}\text{Mg}$. We measured the isotope shift in the $3s_{1/2} \rightarrow 3p_{1/2,3/2}$ transitions in Mg^+ in order to investigate the rms charge radii along the isotopic chain and thus obtain information about changes in nuclear structure. The stable isotopes ^{24}Mg and ^{26}Mg were chosen as reference isotopes and were repeatedly measured during the beamtimes.

Resonances of ^{24}Mg and ^{26}Mg are presented in the lower two traces of Fig. 6. To obtain the isotope shift, the voltage is converted into a frequency scale and the resonance curve is fitted with a Voigt profile. This results in an isotope shift of $3.152(2)(7)$ GHz. The first uncertainty denotes the statistical and the second one the systematic uncertainty caused by the uncertainty of the start potential inside the ionizer tube of about 3 Volt. This $^{24,26}\text{Mg}$ isotope shift was recently measured with high accuracy in an ion trap [38], and the reported result of $3.084905(93)$ GHz deviates from our measurement by 68 MHz.

If we account for the new HV calibration, the two resonance positions are shifted in voltage as shown in the upper two traces of Fig. 6. The crucial point is that this

shift is slightly different for the two isotopes and the value for the isotope shift changes to 3.076(2)(7) GHz which is much closer to the trap measurement. The exit of the hot ionizer tube is at the ISOLDE potential [37] and the polarity for heating the tube is assumed to be such that the exit of the tube is more negative as it seems natural for the extraction of positive ions. Then the ion beam energy should be higher than given by the ISOLDE voltage, which shifts the IS value even closer to the trap results.

This demonstrates the need of a precise voltage measurement and validates the recalibration efforts performed at ISOLDE. Particularly for the spectroscopy on light elements a relative calibration accuracy of the order of 10^{-5} is required.

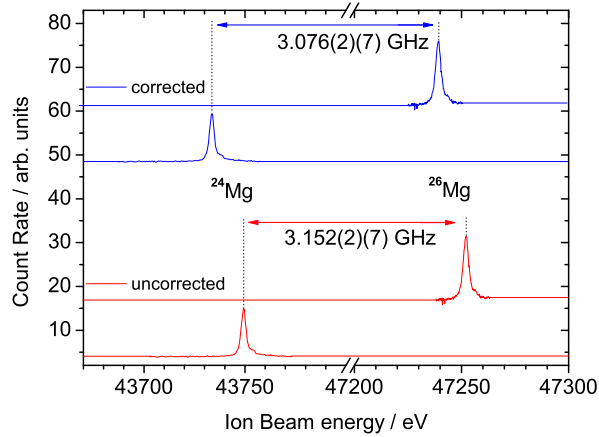


Figure 6: Deviation of first isotope shift measurements on $^{24-26}\text{Mg}$ at COLLAPS from the literature value with (upper traces) and without (lower traces) including the recent voltage calibration.

6. Summary

We have calibrated the high-voltage dividers, used for measuring the acceleration voltage of ISOLDE, against the KATRIN high-precision dividers and found deviations of $2 \cdot 10^{-4}$ and $6 \cdot 10^{-4}$ for the two devices that have been in operation for more than 20 years. The calibrations are in accordance with laser spectroscopic measurements of the ion beam energy using Be^+ isotopes and a frequency comb for optical frequency measurements. Two calibrations within about 18 months have demonstrated that currently only the unit HT1 fulfills the requirements for collinear laser spectroscopy. For HT2 further investigations of the day-to-day and long-term behavior are required before it can be used again for collinear laser spectroscopy.

Applying the new calibration for laser spectroscopic isotope shift measurements of Mg resolved discrepancies initially observed between collinear measurements and recent experiments on laser-cooled ions in a Paul trap.

Experiments using collinear laser spectroscopy similar to those at COLLAPS/ISOLDE are currently being prepared for example at the TRIGA-reactor in Mainz [39], which is a prototype for the LaSpec laser experiment [40, 41] at FAIR, or the BECOLA experiment [42] at NSCL/MSU and later FRIB. At all these places the installation of a good voltage divider is foreseen in order to ensure an accurate knowledge of the ion beam energy and to reach the desired precision for laser spectroscopy on short-lived radioactive isotopes.

7. Acknowledgment

This work is supported by BMBF Contract No.06TU263I, 06UL264I, 06MZ215/TP6 and 06MZ9178I, Helmholtz Association Contract VH-NG-148 and the EU (FP-6 EU RII3-CT-2004-506065). The KATRIN dividers are paid from money coming from our BMBF fundings: 05CK2PD1/5, 05CK5PMA/0, 05A08PM1. Andreas Krieger acknowledges support from the Carl Zeiss Stiftung (AZ:21-0563-2.8/197/1). We acknowledge support from the ISOLDE technical group.

References

- [1] S.L.Kaufmann, Opt. Comm. 17 (1976) 309-312
- [2] G. I. Budker *et al.*, Part. Acc. 7 (1976) 197
- [3] H. Poth, Phys. Rep. 196 (1990) 135
- [4] E.W. Otten and C. Weinheimer, Rep. Prog. Phys. 71 (2008) 086201
- [5] J. Kaspar *et al.*, Nucl. Instr. and Meth. A 527 (2004) 423
- [6] T. Thümmel *et al.*, New J. Phys. 11 (2009) 103007
- [7] R. Neugart, Hyp. Interact. 24 (1985) 159-180
- [8] R. Neugart *Collinear fast-beam laser spectroscopy* Progress in Atomic Spectroscopy, Part D (eds. H.J. Beyer and H. Kleinpoppen) Plenum Press, New York (1987) 75-126
- [9] E. W. Otten *Nuclear radii and moments of unstable isotopes* Treatise on heavy-ion science, vol. 8, Plenum Publishing Corporation (1989)
- [10] J. Billowes *et al.*, J. Phys. G 21 (1995) 701-739
- [11] H. -J. Kluge *et al.*, Spectr. Acta Part B 58 (2003) 1031-1045
- [12] O. Poulsen *et al.*, Nucl. Instr. and Meth. 202 (1982) 503-509
- [13] O. Poulsen *et al.*, Metrologia 25 (1988) 147-153
- [14] S. Götze *et al.*, Rev. of Sc. Instr. 75 (2004) 4
- [15] B. Schinzler *et al.*, Phys. Lett. B 79 (1978) 209
- [16] A. C. Mueller *et al.*, Nucl. Phys. A403 (1983) 234
- [17] G. Ulm *et al.*, Z. Phys. A 321 (1985) 395-402
- [18] R. E. Silverans *et al.*, Phys. Rev. Lett. 60 (1988) 2607-2610
- [19] W. Borchers *et al.*, Phys. Lett. B 216 (1989) 7-10
- [20] W. Geithner *et al.*, Hyp. Interact. 129 (2000) 271-288
- [21] P. Campbell *et al.*, Phys. Rev. Lett. 89 (2002) 082501

- [22] A. Nieminen *et al.*, Nucl. Instr. and Meth. A 469 (2001) 244
- [23] W. Nörtershäuser *et al.*, Phys. Rev. Lett. 102 (2009) 6
- [24] M. Zakova *et al.*, J. Phys. G 37 (2010) 055107
- [25] W. Geithner *et al.*, Hyp. Interact. 127 (2000) 117
- [26] W. Geithner *et al.*, Phys. Rev. Lett. 101 (2008) 252502
- [27] E. Riis *et al.*, Phys. Rev. A 49 (1994) 207-220
- [28] S. Reinhardt *et al.*, Nat. Phys. 3 (2007) 861 - 864
- [29] C. Novotny *et al.*, Phys. Rev. A 80 (2009) 022107
- [30] E. Kugler, Hyp. Interact. 129 (2000) 23-42
- [31] H. -J. Kluge *et al.*, *Proceedings of the Accelerated Radioactive Beams Workshop*, TRI-85-1 (1985) 119, TRIUMF, Vancouver, Canada
- [32] V.I. Mishin, Nucl. Instr. and Meth. B 73 (1993) 550-560
- [33] D.C. Fiander *et al.*, *A 60 kV modulator for the target voltage of an on-line isotope separator*, CERN/PS 92-38, Proc. of the 20th Power Modulator Symposium (1992) Myrtle Beach, USA
- [34] C.A. Hamilton *et al.*, Rev. Sci. Instrum. 71 (2000) 3611-3623
- [35] B.D. Josephson *et al.*, Phys. Lett. 1 (1962) 251-253
- [36] M. Beck *et al.*, J. Phys.: Conference Series 203 (2010) 012097
- [37] U. Köster *et al.*, Spectr. Acta Part B 58 (2003) 1047-1068
- [38] V. Batteiger *et al.*, Phys. Rev. A 80 (2009) 022503
- [39] J. Ketelaer *et al.*, Nucl. Instr. and Meth. A 594 (2008) 162-177
- [40] W. Nörtershäuser *et al.*, Hyper. Interact. 171 (2006) 149-156
- [41] D. Rodriguez *et al.*, Eur. Phys. J. Special Topics 183 (2010) 1-123
- [42] K. Minamisono *et al.*, Proc. Insti. Nucl. Theory 16, (2009) 180
- [43] J. Schipper *High tension control system for the on-line isotope separators* - Isolde PS/PO Note (2002) 207